Modeling and compensation of cutting-forces generated during the EDM process for ultra high-precision robots

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Abstract

This work deals with the calibration of industrial robots operating at sub-micrometric precision. We demonstrate that the cutting-forces generated by the robot manufacturing process cause a significant deformation of the robot geometry, lowering its absolute accuracy. Then, we propose a way of studying and modeling such deformations, in order to compensate them during the robot usage. We have taken the micro electro-discharge machining process on the robot Agietron micro-nano as a case study and we have used an ultra high-precision measuring system to evaluate the deformations due to cutting-forces. Finally, we have built a mathematical model of the robot physical behavior and we have implemented it in the robot controller, in order to compensate the deformations in real-time.

1 Introduction

Robot calibration is a process that permits to increase robot accuracy. It consists in modeling and compensating the sources of inaccuracy that affect robot positioning [1]. Beyond geometric errors and thermal drift, cutting-forces due to the robot manufacturing process cause a significant loss of accuracy [2]; in this article, we will focus especially on this issue. The robot considered in this work is an Agietron micro-nano (fig. 1), a parallel robot based on the professor Clavel's Delta kinematic [3][3'], entirely built in titanium and equipped with flexure hinges joints. The robot has a working space of ~1 cm^3 and a size of ~20x20x25cm. The features of this robot have been drawn on to build a new modular concept of design that will bring more flexibility in robot industrial applications [4].

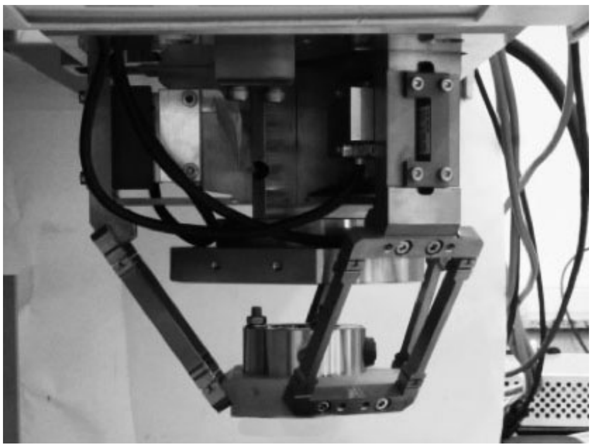

Figure 1 The robot studied in this work, the Agietron Micro-Nano (delta kinematic).

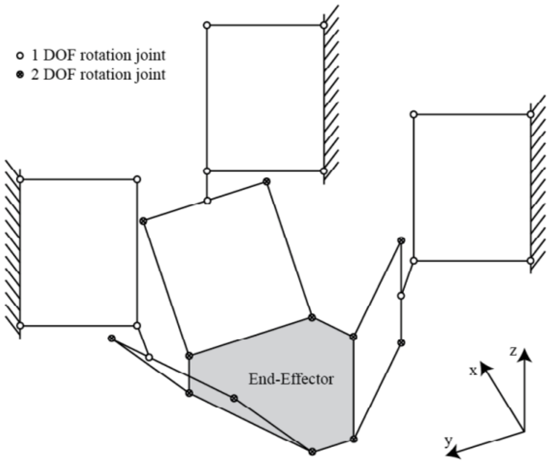

Figure 2 Kinematic chain of the robot.

The micro-EDM process is used for cutting complex shapes and thin walled configurations without distortion. It is recommended for hard materials or for materials typically machined by grinding [5]. The process is suited for applications characterized by extremely exacting tolerances (accuracy ~1 μm). Since it is a contactless process, it is also well suited for making fragile parts that cannot take the stress of a normal machining process. To perform it, an electrode or a wire is mounted on the robot end-effector. A controlled electrical spark is used to erode away from the manufactured object any material that can conduct electricity. A series of discharges takes places between the electrode and the conductor while the robot is moving along the desired trajectory.
The purpose of this article is to evaluate the deformations caused by the micro-EDM process and to propose a way to compensate them, in order to maintain the robot accuracy unaffected during the industrial process.

2 The measuring system

A 6 DOF measuring system has been conceived to measure translations and rotations at very high level of precision (fig. 3).

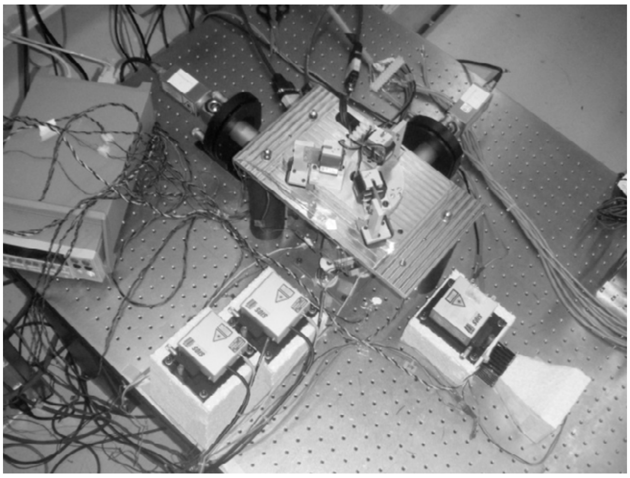

Figure 3 A picture of the system.

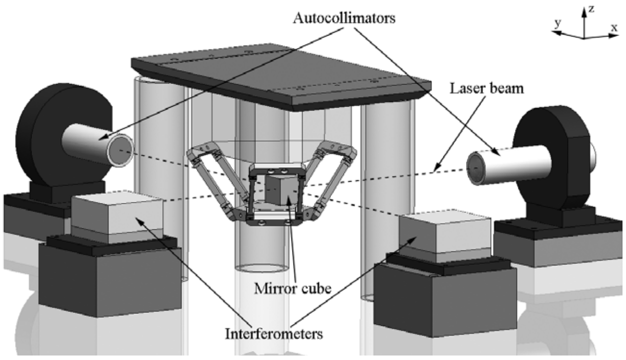

Figure 4 The instruments measuring horizontal translations and all the rotations.

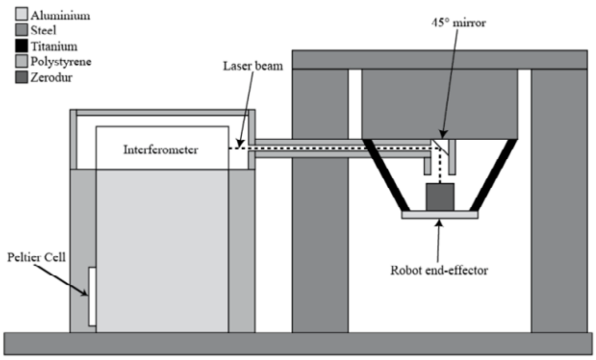

Figure 5 Scheme of vertical axis measurement.

A mirrored cube is glued on the end-effector of the robot. It will be use to reflect the beams of the measuring instruments. Furthermore, it defines the origin and the frame of the system. The cube is built in Zerodur®, a material with an extremely low thermal expansion coefficient (~0.02 x 10-6/K at 0-50°C). The surface roughness of the mirrored facets is 30 nm.

Translations are measured using 3 laser interferometers (SIOS SP-2000, resolution of ~1.24 nm, wavelength of ~633 nm, stroke of ~2 m) arranged orthogonally. However the three interferometers are mounted horizontally. While the interferometers measuring the horizontal axes have direct access to the cube facets (fig. 4), the vertical axis is measured using a 45° mirror (fig. 5).

Rotations are measured using 2 autocollimators (Newport LDS-1000 Autocollimator, resolution of 0.02 arcsec, stroke of ±400 arcsec, around the two axes perpendicular to the measuring beam), capable of measuring in total 4 DOF (the vertical axis measure is redundant). The principal aim of the rotation measurement is to compensate the end-effector parasitic rotations. In fact, those rotations affect the interferometer reading, adding the so called cosine error [6]. Errors dues to parasitic rotations are corrected in real-time. To avoid measuring the drift of the measuring system, we stabilize the instruments supports, with a maximum error of ±0.01 °C. The temperature control is done using a Peltier cell glued on the support.

Finally, the entire measuring loop is equipped with 13 temperature sensors, used to map all the thermal variations of different parts of the system.

3 The force simulator device

To study how cutting-forces generated during micro-EDM process deforms the robot, we needed a device that permits us to simulate the manufacturing conditions while the measuring system is operational. The device must have the following characteristics:

- Since micro-EDM is a contactless process, the device must apply forces without touching the robot.
- The forces applied on the end-effector must be dimensioned to be of the same order of the micro-EDM's ones.

Therefore, we have built a device composed by three inductances mounted right under the robot end-effector. Three permanent magnets have been fixed on the end-effector, in axis with the inductances (Fig. 6).

By applying a current to the inductances, we can generate repulsive forces and momentums on the end-effector.

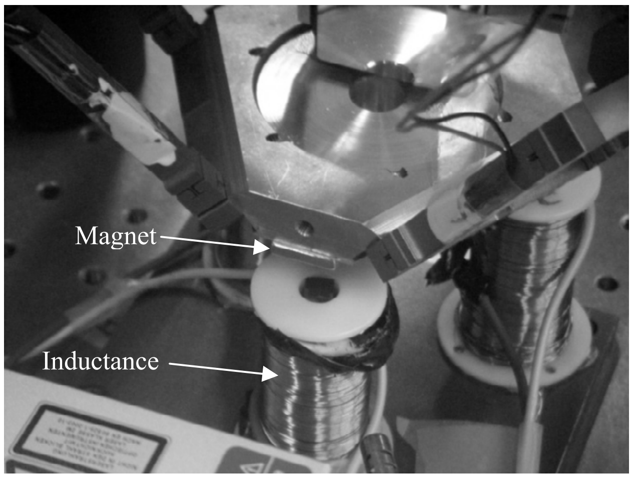

Figure 6 The force simulator system mounted under the robot end-effector.

Those forces are dimensioned to be similar to the ones generated during the micro-EDM process (around 1-2 N [7]). The system have been tested and measured before mounting it on the robot in order to measure which current and which distance inductance-magnet is needed to achieve the desired force of 2 N.
Each coil is composed by 800 spires. The wire that we have used is 0.5 mm thick. A ferrite core has also been introduced in the coil center. The distance from the magnets must be between 10 mm and 15 mm. The current passing in each coil is limited to 2 A. The magnets attached under the end-effector are 15x15x3 mm Nickel-plated elements, with an approximate strength of 34 N when in contact. A conductive tube has been mounted around each coil to concentrate the magnetic lines fields on the magnet mounted on the robot.

3.1 Preliminary test

The first test has been done to see if micro-EDM process causes a significant deformation on the robot structure that justifies calibration.
We applied a current of 2 A on each coil, generating a repulsive force of approximately 2 N on the end-effector. We obtained a displacement of 291 nm along X axis, 700 nm along Y axis and 168 nm along Z axis. Notice that during the test the robot is under control and steady on a known position. This means that the drift that we have generated is in the robot structure, between the encoders and the end-effector. The entity of such deformation justifies keeping it in account in the calibration process.
This preliminary test permits us also to understand that a thermal shield is needed to obtain better measures. In fact when a current is applied to the coils, they generate heat that deforms the robot structure. This effect has been avoided by closing the force simulator system in an insulate box.

3.2 Repeatability test

A repeatability test on the displacement caused by the force simulator device has been carried out. In the test, the robot is kept still in one position. Then, a force of 2 N is imposed. The goal of this experiment is to see how the displacements caused by the force simulator are repeatable. This test will also give us the limit of the calibration attainable.

3.2.1 Repeatability test results

In fig. 7 we can see the result of the test. For 25 points, it is plotted the difference in positioning between the case in which no force is applied and when a force of 2 N is applied. We have a repeatability of ±46 nm for X axis, ±36 nm for Y axis and ±61 nm for Z axis, considering the 90% of the points (1.645σ). This is the limit of the accuracy that we could reach with this system after the calibration process.

3.3 Force direction test

In all the workspace of the robot, it has been measured the position difference while no force is given and while a force of 2 N is given. The difference between the two positions has been used to calculate the direction of the force vector in each spot where the test has been done.

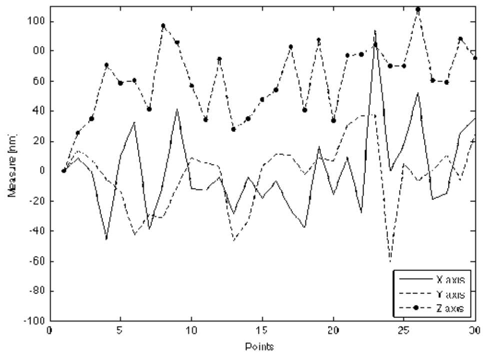

Figure 7 Repeatability test.

3.3.1 Force direction results

In figures 8a we can observe the robot workspace from the top. The workspace of the robot is the sum of two pyramids having a hexagonal base (see fig. 8b). This is a direct consequence of the robot geometry. We observe (especially in fig. 8a) that the force direction component along Y axis is more important of the component along the others two axes. We see also (fig. 8b) that the force always goes from down to the top: the force is always repulsive. Reading carefully the data we can observe that the repulsion is more important in the lower part of the workspace, where the coils are nearer to the magnets on the end-effector. Also if the force is not completely equal to the micro-EDM case, we believe that this work is still representative of a repulsive force calibration.

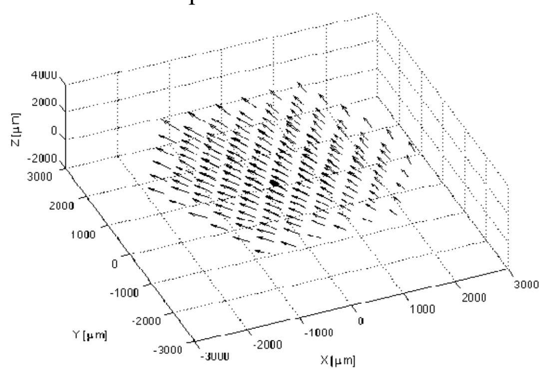

Figure 8a Force direction test, seen from a vertical position.

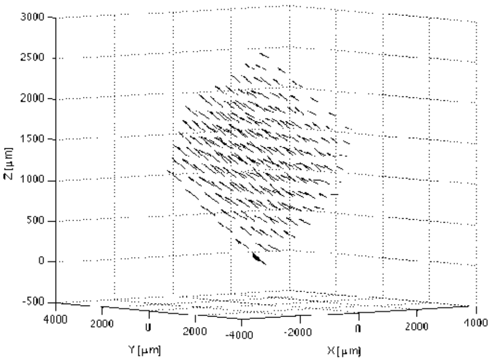

Figure 8b Force direction test, seen from a horizontal position.

4 Measures

To collect the deformations measurements, the robot has been displaced in 216 positions, a motor coordinates grid of 6x6x6 positions. In each of them a set of forces has been imposed to the end-effector (0, 0.5, 1, 1.5 and 2 N), and a measure for each force has been taken. In total 1080 measures have been acquired. This set of data will be used only for calibration.

A second set of data has also been taken. This time the set is composed by 125 positions (a grid of 5x5x5 position). Notice that those points are not coincident with the one of the first set. Also in this case several forces have been imposed to the end-effector (0, 0.5, 1, 1.5 and 2 N), obtain in total 625 points. This data set will be used only for the validation of the model.

For each point, a set of four measures is acquired. The standard deviation of those four points is calculated. This value is never superior to 20 nm.

5 Data Processing and calibration

Following the calibration procedure described in [8], the next step is to use the collected measurements to build a calibrated model of the robot. This model will have as input the desired end-effector position (X, Y, Z) plus the value of the force applied on the end-effector. As output, it will return the motor coordinates (q_1, q_2, q_3) corresponding to the desired position (compare with fig. 12b after). In robotics, this is called “inverse geometric model” (eq. 1), IGM.

$$q_1, q_2, q_3 = f(X, Y, Z, F) \qquad (1)$$

A model built in such way will keep in account the geometric features of the robot and the deformations caused by the cutting-forces. This model will be done multiplying the variables seen before (the measures and the forces), and finding the good coefficients to fit the relation [7]. To perform the coefficients research, we will use the “stepwise regression” algorithm (Matlab®, Statistics Toolbox™). This algorithm has the capability of adding or removing terms from a multi-linear model. This is done comparing the statistical significance of the terms in a regression. The algorithm starts with an initial model that is compared with larger or smaller models. At each step, a coefficient is added to the model, thus, it is compared the final error with or without this last coefficient. If there is an improvement in the prediction, the coefficient is kept. Otherwise the coefficient is discarded. For the coefficients that are already in the model it happens the same: if the influence of any coefficient is under a certain threshold, the coefficient is rejected.

Depending on the terms included in the initial model and the order in which terms are moved in and out, the method may build different solutions from the same set of terms. The method terminates when any single step improves the model prediction capability. There is no guarantee that a different initial model or a different sequence of steps will not lead to a better fit. In this sense, stepwise models are locally optimal, but may not be globally optimal.

The stepwise regression algorithm has been chosen for two reasons: firstly it automatically deletes useless parameters, keeping the robot model computationally fast. Secondly, the algorithm converges and gives a solution in some seconds. On the contrary, algorithms tested in previous works (neural networks, gradient descent based parameters research, genetic algorithms and splines optimization) take some hours to give a solution.

5.1 Generating the data for the calibration

The first step that we do is separate the relation (1) in three different one. In this way the problem will be less complex. Basically, what we do here is to calibrate each motor separately (eq. 2):

$$\begin{cases} q_1 = f(X, Y, Z, F) \\ q_2 = f(X, Y, Z, F) \\ q_3 = f(X, Y, Z, F) \end{cases} \qquad (2)$$

For each equation of the system we will consequentially find different coefficients.

We will now focus on how we calibrated one single axis; the procedure is the same for the remaining two.

What we want is a model that, given the desired end-effector coordinate and the force acting on the end-effector in that moment, it returns the motor coordinate for the motor q_1. For the moment we have only 4 variables, so we will use them to generate new ones: this is done by multiplying them together, in order to see if the model fits the correlation of more complex variables.

From three interferometer readings (1st order) we generate terms of the 2nd and 3rd order:

1st order: X, Y, Z
2nd order: $X^2, Y^2, Z^2, XY, YZ, XZ$
3rd order: $X^3, Y^3, Z^3, XYZ, X^2Y, X^2Z,$
Y^2X, Y^2Z, Z^2X, Z^2Y

From the departing 3 readings, we have generated 16 new correlation variables. In total, we have 19 pure geometrical variables.

Doing the square and the cube of the force, we obtain three new variables: F, F^2, F^3.

Multiplying the 19 geometrical variables with the force ones, we obtained 57 new variables.

Adding all the variables together gives a final number of 79 variables. The calibration of one axis can be seen as the research of the coefficients $a_1, \dots, a_n$ that satisfy the following relationship (eq. 3):

$$\begin{bmatrix} q_1 \\ \cdots \\ q_m \end{bmatrix} = A \begin{bmatrix} a_1 \\ \cdots \\ a_n \end{bmatrix} + b \qquad (3),$$

$$A = \begin{bmatrix} X_{1,1} & \cdots & X_{1,1}^2 & \cdots & F_{1,1} & \cdots \\ \cdots & & \cdots & & \cdots & \\ X_{1,m} & \cdots & X_{1,m}^2 & \cdots & F_{1,m} & \cdots \end{bmatrix} \quad (4),$$

where $[q_1 \quad \cdots \quad q_m]^T$ is the vector of the motor coordinates q_1, A is an *m x n* matrix containing the values of the all interferometers readings, force values plus all the built coefficients corresponding to the motor coordinate plus all the correlated coefficients we want to fit, $[a_1 \quad \cdots \quad a_m]^T$ is a vector containing the parameters that "stepwise regression" has to fit to make the (3) true and b is an offset (the last coefficient to be found). In this case m = 1080, the total number of measures used for the calibration.

Stepwise regression algorithm has been launched to solve this problem and only 19 parameters have been kept. The measurements in the calibration set have been fitted with an error of ±105 nm in the 90% of the points (1.645σ).

Regarding the q_2 and the q_3 motor coordinates, we had respectively a model composed by 25 and 26 parameters, with an error in predicting the calibration set of ±88 and ±81 nm (fig. 9).

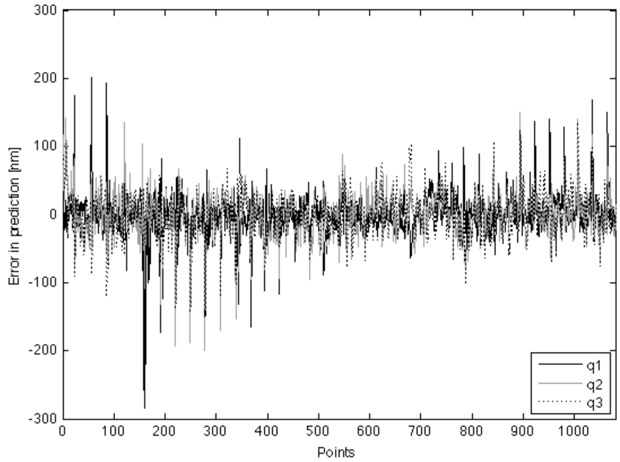

Figure 9 Calibration results in the calibration dataset.

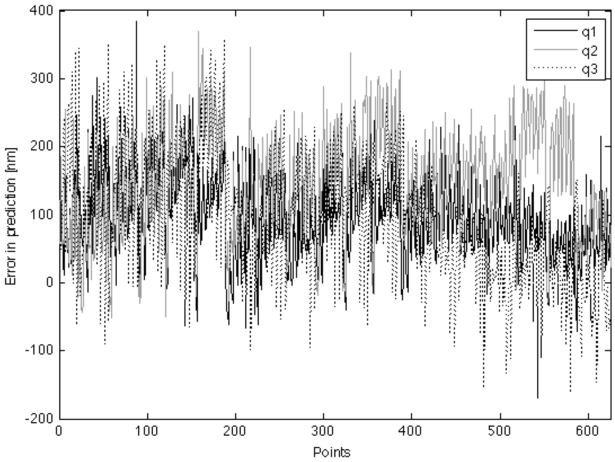

Figure 10 Calibration results in the validation dataset.

5.2 Calibration results

The parameters found before are finally used with the validation set. As seen before, this data has not been used to calibrate the robot, so it will be the final demonstration of its calibration.

Using the validation error we have a final error of ±159 nm along the q_1 axis, ±143 nm along the q_2 axis and ±142 nm along the q_3 axis, considering an interval of confidence of 90 % (1.645σ) (fig. 10).

To confirm that we have to keep in account cutting-force reading to perform calibration, we have built a model that contains only geometric parameters and discards force parameters. This model contains only 16, 16 and 20 parameters respectively for q_1, q_2 and q_3 axes. The results were really bad compared to the one that keeps in account the force: ±160 nm along q_1 axis, ±376 nm along q_2 axis and ±1789 nm along q_3 axis. This last value is in consequence that the force generate by the force simulator is almost completely discharged on the motor q_3 (fig. 11). This definitely confirms that cutting-forces calibration is needed.

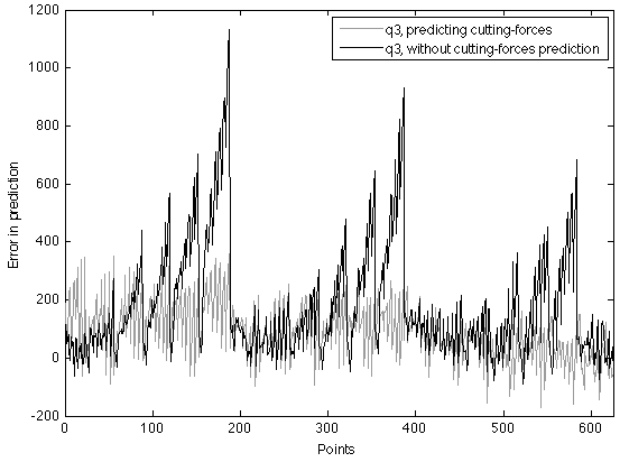

Figure 11 Comparison between the prediction of q_3 axis with prediction of cutting-forces and without prediction of cutting-forces.

6 Conclusions

We have demonstrated that the force calibration procedure is effective for a 3 DOF ultra high-precision robots. We have also seen that using a simple model composed in total by 70 parameters we can guarantee a robot precision in the order of 0.1 μm.

6.1 Industrial application

To perform the force calibration on a system without using the force simulation device, it is possible to work in two ways (refer to fig. 12, a and b):

a) Use the force reading of the motor to build the inverse geometric model. This is the best and easier way to implement it. Nevertheless it is necessary that motors have a very low hysteresis and that they are repeatable.
b) Install a force sensor between the robot end-effector and the tool-tip. The reading of this sensor will be used to feed the inverse geometric model with the force acting on the robot. This method is worst in

comparison to the first one, because it is impossible to detect deformations of the tool-tip.

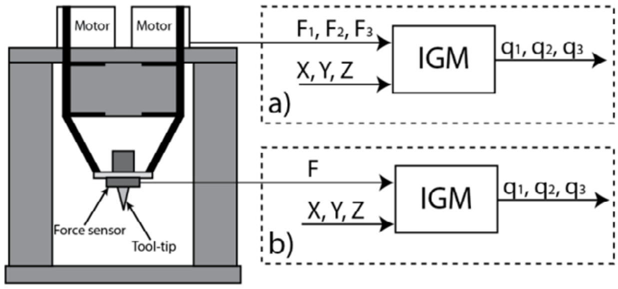

Figure 12 Two ways of using the force calibration.

6.2 Future work and conclusion

In the future we will improve this work performing the following steps: we will study how to calibrate the robot while the environmental conditions of the room are changing and the cutting-forces are acting on the robot.

Furthermore, it will be possible to use a more sophisticated system to simulate forces: depending on the robot application, it can be necessary to study more aspects related to force (direction, modulus and momentum).

The original contribution of this work are the development of a 6 DOF ultra high-precision measuring system, the development of a contactless simulator device to apply forces on a robot end-effector, the calibration of a 3 DOF ultra high-precision robot while cutting-forces are acting on the end-effector.

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7 Literature

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